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FINAL TECHNICAL SUMMARY REPORT

DEVELOPMENT PROGRAM ON LONG TERM TESTING OF CYLINDRICAL THERMIONIC DIODES AND THE IRRADIATION OF FUEL AND INSULATORS

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GENERAL ELECTRIC COMPANY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-2544
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TOPICAL REPORT

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DEVELOPMENT PROGRAM ON LONG TERM TESTING OF CYLINDRICAL THERMIONIC DIODES AND THE IRRADIATION OF FUEL AND INSULATORS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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CONTENTS

ABSTRACT

This document is the Final Technical Summary Report describing the work accomplished under a research and development program on long term testing of cylindrical thermionic diodes and the irradiation of fuel and insulators. Details of the program results were published in four topical reports:

NASA CR-72282, "High Temperature Compatibility of Uranium Dioxide (UO_2) with Tungsten–25 Weight Percent Rhenium (W-25 w/o Re)." This report includes results from tests performed at temperatures of 1300°C to 2200°C in cesium and vacuum environments for times up to 5000 hours.

NASA CR-72334, "Irradiation of High Purity Alumina." In-situ measurements of electrical properties of alumina tested at temperatures of 800°C to 1000°C to a fast neutron (>1 MeV) dose of 1.6×10^{20} were reported.

NASA CR-72355, "Development and Evaluation of Cylindrical Thermionic Converters" (CRD). Out-of-pile converters were tested to evaluate performance, reliability and life.

NASA CR-72356, "Irradiation of UO_2 Fuel Clad with Tungsten–25 Weight Percent Rhenium" (CRD). An in-pile irradiation to fuel burnups of 2.16×10^{20} fissions/cc at temperatures of 1650°C was performed.

SUMMARY

A research and development program on the long term testing of cylindrical diodes and the irradiation of fuel and insulators was performed. Studies were made to determine the high temperature compatibility between UO_2 and W–25 w/o Re cladding. A 0.020-inch-diameter vent hole was located on one end cap of each W–25 w/o Re capsule. UO_2 of stoichiometric composition was placed in each capsule. There was no evidence of gross interaction between the UO_2 and the cladding in out-of-pile isothermal tests at 1800°C for 5000 hours, 2000°C for 3000 hours, and 2200°C for 1000 hours in a cesium vapor. Tests were also performed on cermet samples of 60 and 70 volume percent UO_2 in a tungsten matrix and clad with W–25 w/o Re. The cermets were tested at 1800°C and 2000°C for 500 and 389 hours, respectively, in a vacuum environment. Cracking of the clad occurred in all of the samples; this was attributed to the large mismatch in thermal expansion between the cermet and the clad.

The objective of the alumina irradiation task was to obtain engineering design data concerning the irradiation effects on the properties of Al_2O_3 at temperatures of 800°C to 1000°C. An irradiation capsule was designed to allow for the in-situ measurements of the electrical resistivity and voltage breakdown. Eight high purity alumina (Lucalox) specimens were irradiated for 1290 hours in NASA/Plum Brook Reactor to a total fast integrated neutron flux of 1.6×10^{20} nvt. In-pile electrical resistivity was approximately a factor of five higher than the out-of-pile data and there was no evidence of voltage breakdown when 300 V d.c. was applied to each specimen. Post-irradiation examinations revealed that the alumina turned from a milky-white to a dark-gray color; no dimensional changes occurred and four specimens were crack free. The total fast integrated flux for in-pile thermionic designs having 10,000 hour life will be approximately an order of magnitude higher than tested herein.

The purpose of the cylindrical theremionic converter task was to determine device performance and reliability by out-of-pile screening tests. A converter and supporting components, closely simulating a converter designed for a thermionic reactor, were achieved through an evolutionary program of design, fabrication and testing. Seven converters with concentric tungsten emitters and niobium collectors were tested. Test times up to 8055 hours with an average test time of 3525 hours were achieved. All tests with one exception were terminated because cesium leaked into the electron bombardment heating equipment through a tantalum isolation thimble. Repeatable fabrication of converters with reproducible performance characteristics was obtained. Performance tolerance of $\pm$ 10% was achieved.

The objective of the irradiation task involving UO_2 fuel clad with W–25 w/o Re emitters was to determine its structural integrity, the behavior of fission products that escaped through three 0.020-inch vent holes and the UO_2-clad compatibility to fuel burnups greater than 1×10^{20} fissions/cm^3 at clad temperatures of 1650°C. Four emitter specimens were irradiated for a total of 3340 hours. Post-test examination revealed (1) a release of fission gasses greater than 77%, (2) the emitters experienced dimensional changes up to 0.050 inch on diameter, (3) fuel burnups ranged from .92 to 2.16 fissions/cm^3, (4) there was no evidence of any interaction between the UO_2 and W–25 w/o Re clad, and (5) the vent holes in all specimens were completely open.

INTRODUCTION

In the design studies of in-core nuclear thermionic space power systems, key technology areas of the reactor were identified. These include such technology areas as materials, nuclear fuels, converters, reactor physics, control, etc. Some of these technology areas were selected as the subject of this research and development program on the long term testing of cylindrical diodes and components, and the irradiation of fuel and insulators. The program objectives and scope of work are outlined below.

PHASE A

Basic thermionic converters, closely simulating a thermionic reactor application, will be developed through an evolutionary program of design, fabrication, testing and evaluation.

Task 1

Three cylindrical converters will be designed, fabricated and life tested to demonstrate the life of the collector, emitter, spacing assemblies and related internal components. Components will be dissected to investigate causes of any deterioration or failure.

Task 2

Three converters similar to those in Task 1 will be designed, fabricated and life tested. The design will include a mock-up of an intercell assembly for multicell application. This intercell assembly will include provision for electrode spacing, back emission shields, and intercell connections. The intercell connections will not be required to carry current. The components will be dissected to investigate causes of any deterioration or failure.

Task 3

A detailed design analysis (including thermal and stress analyses) will be performed and procedures will be prepared for the fabrication and assembly of a three-converter series connected segment of a nuclear thermionic fuel element (TFE).

Task 4

A thermionic converter which includes a mock-up of an intercell assembly based on the concept of Task 3 will be designed, fabricated and life tested. The converter test will be conducted

at an emitter temperature of 1700°C and a collector temperature of 900°C for 2000 hours or until failure, whichever occurs first. The intercell electrical connections will be active; i.e., current conducting. The converter will be dissected to investigate causes of component failure and any deterioration.

Task 5

Two converters will be designed, fabricated and life tested to investigate the effect of uranium dioxide fuel in a W–25 w/o Re clad emitter on thermionic performance during an extended period (4500 hours) of converter operation at an emitter temperature of 1800°C and a collector temperature of 1000°C. The converters will be dissected to investigate failures or physical changes.

PHASE B

Fuel/clad emitters will be developed and fabricated and the long term effects of thermal and irradiation exposures on them will be studied.

Task 1

Twelve W–25 w/o Re fueled specimens will be designed, fabricated and tested in high temperature furnaces in the temperature range 1800°C to 2200°C for periods up to 5000 hours in a cesium vapor environment. A representative number of the specimens will be subjected to detailed chemical and metallurgical analyses to determine the nature and extent of any fuel/clad interactions and the effects of venting the fuel to the cesium environment.

Task 2

A capsule assembly containing four specimens of uranium dioxide fuel/clad in vented W–25 w/o Re will be fabricated and irradiated in the Plum Brook Reactor Facility. Post-test analyses will be performed on the irradiated specimens to determine the dimensional stability, structural integrity, and extent of any interaction between materials.

PHASE C

High purity alumina specimens will be irradiated at elevated temperatures in the Plum Brook Reactor in a vacuum environment. Electrical resistivity and breakdown voltage will be measured during irradiation. A post-irradiation examination will be performed to determine the changes in physical properties of the specimens.

The technical objectives of these program tasks have been achieved and the results of this research and development program have been published in four topical reports.

"High Temperature Compatibility of UO_2 with Tungsten-25 Weight Percent Rhenium," by R. D. Ekvall and J. O. Hegland, NASA CR-72282, GEST-2099, May 1967.

"Irradiation of High Purity Alumina," by T. L. Gregory, NASA CR-72334, GEST-2101, June 1967.

"Irradiation of UO_2 Fuel/Clad with Tungsten-25 Weight Percent Rhenium," by T. L. Gregory, R. F. Boyle, and J. C. Danko, NASA CR-72356, GEST-2100, (CRD), December 1967.

"Development and Evaluation of Cylindrical Thermionic Converters," NASA CR-72355, GEST-2098, (CRD), by J. M. Scott, J. M. Case, and D. L. Gilliland, December 1967.

This document, the final technical summary report, summarizes the results reported in these topical reports.

TECHNICAL REPORT SUMMARIES

HIGH TEMPERATURE COMPATIBILITY OF UO_2 WITH TUNGSTEN-25 W/O RHENIUM

Work performed under this task was directed toward the determination of the high temperature chemical compatibility between UO_2 and W–25 w/o Re cladding. This consisted of two parts: (1) Isothermal testing of vented and unvented UO_2 clad in W-25 w/o Re in a cesium environment for times to 5000 hours at temperatures from 1800°C to 2200°C. In addition, thermal cycling tests of similar materials were performed in a vacuum environment. (2) Testing of unvented W-UO_2 cermets containing 60 and 70 volume percent UO_2 and contained in W-25 w/o Re at temperatures of 1800°C to 2000°C for times of 500 and 389 hours, respectively, in a vacuum environment.

Under Part 1, W-25 w/o Re containers of approximately 0.50-inch-diameter by 0.50-inch-long with a 0.020-inch-thick wall and a 0.030-inch-thick end cap were used. A 0.020-inch-diameter vent hole was located on one end cap for the vented capsules. Uranium dioxide pellets of stoichiometric composition were placed in the containers and tungsten inert gas welding (TIG) was used to join the end caps to the tube section. The test samples were enclosed in a tantalum (Ta) test chamber which contained a cesium atmosphere. This test chamber was inserted in a vacuum furnace for the isothermal testing.

Capsules isothermally tested for times of 5000 hours at 1800°C, 3000 hours at 2000°C, and 1000 hours at 2200°C changed very little in dimension and weight. The visual observations of the capsules revealed no surface defects and no evidence of attack by the cesium vapor. The vent holes were not plugged, although a few vents contained an internal peripheral metallic deposit. The cesium vapor was very effective in suppressing the evaporation loss of UO_2 through the vent hole relative to the UO_2 loss into vacuum.

In all the capsules examined there was no evidence of gross interaction between the UO_2 and cladding although evidence of a superficial interaction on the inside surface of the cladding was observed in the capsules tested at 2200°C. This interaction zone was approximately 1 micron thick and consisted of a fine grain boundary penetration of UO_2 and a small amount of a metallic phase that may be free U. Varying degrees of porosity were observed in the cladding and were more pronounced for the capsules tested for long times and at high temperatures. Abnormal grain growth occurred in the cladding of some of the capsules. Spectrographic and chemical analysis of the cladding indicated that a small pickup in oxygen (55 to 100 ppm), uranium (48 to 360 ppm), and tantalum (~900 ppm, probably from the chamber) had occurred.

As a result of the isothermal testing, the UO_2 pellets exhibited grain growth. The largest grain size was observed in the high temperature (2200°C) capsule. In addition, free U particles were detected. The origin of the U particles is related to the formation of sub-stoichiometric UO_{2-x} at high temperatures; upon subsequent cooling to room temperatures, free U is precipitated as fine particles randomly dispersed in UO_2. A nonmetallic phase observed in the UO_2 was identified as alumina (Al_2O_3).

In Part 2, cermet samples of 60 and 70 volume percent UO_2 in W were inserted into containers which were structurally and chemically identical to those used in Part 1. Bonding of the cermet to the cladding was achieved by hot isostatic treatments at 1650°C in 10,000 psi helium.

The clad cermets were tested at 1800°C and 2000°C for 500 and 389 hours, respectively, in a vacuum environment. The cermets were to be tested for times to 1000 hours at both test temperatures. However, testing of all the samples was terminated prematurely; extensive container cracking occurred in all samples. All dimensions of the samples increased; the lengths from 0.4 to 2.4 percent and the diameters from 0.6 to 2.4 percent. Metallographic observations revealed that the W-25 w/o Re cladding was no longer bonded to the cermet and that UO_2 evaporated through the cracked region in the cladding.

The reason for the failures is believed to be related to the large difference in the thermal coefficient of expansion between the cermet and the cladding. The linear thermal expansion of the W-60 volume percent UO_2 cermet is approximately 30% greater than the W-25 weight percent Re cladding at 1800°C to 2000°C. Microprobe analysis revealed essentially no change in composition of the cladding.

IRRADIATION OF HIGH PURITY ALUMINA

Insulator materials for nuclear thermionic applications must have properties to satisfy such characteristics as: (1) chemical compatibility with cesium vapor and refractory metals, (2) high electrical resistivity and voltage breakdown, (3) resistance to radiation damage, and (4) good fabricability. A candidate material for this application is high purity alumina (Al_2O_3). The effects of the nuclear environment on the electrical characteristics, dimensional stability and thermal-mechanical integrity must be known and an irradiation program was performed accordingly.

The objective of this program was to obtain engineering data on high purity alumina properties as a function of exposure in a nuclear environment with the test conditions being consistent with those required in thermionic applications.

High purity (99.5%) alumina specimens, nontranslucent high-strength-grade Lucalox was used in the experiment. Chemical and metallographic analysis was performed prior to irradiation. The only significant impurity detected was 5000 ppm of magnesium (used as a densification additive). The material was single phase alpha with a small amount of isolated porosity and a uniform grain size with an average grain diameter of approximately 0.0005 inch. The specimen dimensions were 0.750-inch long, 0.625-inch outside diameter, and 0.030-inch-thick wall. A lip of approximately 1/16 inch was incorporated in the design of the specimen to facilitate mechanical assembly.

The irradiation capsule was designed to accommodate eight alumina specimens. The capsule assembly consisted of an inner electrode of Kovar, the Lucalox specimen, and an outer molybdenum electrode. Located immediately outside the molybdenum electrode were four segments of high purity alumina serving as isolation insulators, which were supported by fluted stainless steel retainers which also served as controlled heat conduction paths. The capsule instrumentation consisted of the continuous common Kovar electrode, a nickel electrode measurement wire that was welded to each of the molybdenum electrodes and the common center electrode. A nickel flux wire was inserted down the center hole of the Kovar inner electrodes. Four Inconel sheathed Pt versus Pt-13% Rh thermocouples were used to measure four of the inner electrode temperatures during operation. The entire assembly was contained in a stainless steel tube approximately 40 inches long in order that the vacuum-tight electrical feedthrough consisting of 15 individual ceramic-to-metal seals be positioned in a low temperature, low neutron flux region. A dummy electrical lead was installed in the ceramic-to-metal seal along with a thermocouple to measure the lead and seal leakage so this could be subtracted from the measurements made on the specimen. The main source of heat was provided by the gamma heat of the reactor. An electrical heater was located on the outside of the stainless steel vacuum container to provide a fine temperature control. A stainless steel containment provided the barrier between the vacuum container and the reactor coolant. Helium gas at about 175 psi provided the heat transfer medium from the vacuum container to the reactor coolant.

All temperatures were recorded on a multipoint recorder. Leakage current through the alumina specimens was measured by an electrometer. Direct current voltage was applied by a regulated power supply. The trim heaters in the capsule were powered by a variable transformer. The voltage from the common center electrode to each individual outer electrode was supplied

by the power supply through a selector switch to select the electrode for individual measurements. The currents from the instrumentation leads were measured with an electrometer circuit. The lead resistances were on the order of 10^6 ohms, while the resistance of the ceramic-to-metal feed-through was on the order of 10^5 ohms higher than the specimen resistance at temperature.

An instrumented mock-up of a single specimen assembly was fabricated and tested out-of-pile in a vacuum bell jar. The purpose of this test was to determine the heat transfer characteristics and the adequacy of the capsule design. The test results indicated that the heat transfer and capsule design were satisfactory. During this test, electrical resistivity measurements were performed on the alumina specimen. There was scatter in the data points; however, the results compare favorably with published data. Typical values are presented in Table 1 below.

TABLE 1. Electrical Resistivity Values* of Alumina (ohm-cm)

	600°C	800°C	1000°C
Lucalox Test (Out-of-Pile)	3×10^9	1×10^8	1×10^7
Published Data	2×10^9	3×10^7	2×10^6

* Average values in the scatter band of data.

During the irradiation, measurements were made of electrical resistivity and breakdown voltage characteristics. The irradiation facility provided a fast flux of approximately 4×10^{13} nv with neutron energies greater than 1 MeV and a thermal flux of 2×10^{14} nv. The gamma heating was in the range of 4 to 6 watts per gram. Specimen test temperatures ranged from 800°C to 1000°C during the course of the irradiation. The in-pile electrical resistivity was approximately a factor of five higher than the out-of-pile data. However, the slope of the electrical resistivity plotted as a log function of temperature is the same for in-pile and out-of-pile data. The test data also indicate that for the total exposure of 1290 hours, the total integrated neutron dose did not appear to change the resistivity of the specimens. The total fast integrated neutron flux was approximately 1.6×10^{20} nvt for the highest exposure to about 1.4×10^{20} nvt for the lowest exposure. With the exception of one specimen, there was no evidence of voltage breakdown when 300 V d.c. was applied to each specimen. In one specimen at an exposure of 1×10^{20} nvt, a 1/8 ampere fuse in series with the electrode measurement line failed at 270 volts indicating an electrical breakdown. After the fuse was replaced, the same events occurred. However, electrical resistivity measurements performed on the specimen resulted in values identical to those obtained prior to the failure of the fuse. Post-irradiation examination failed to yield any evidence of an electrical breakdown of the aluminia. Insulators for in-pile thermionic designs having a life of 10,000 hours will be subjected to a fast neutron fluence of 2×10^{21} nvt or higher.

[redacted]

Post-irradiation examination was performed on the capsule. Visual observations and examination of the capsule exterior revealed that the heater, instrumentation and lead vacuum seal were not damaged. The capsule was disassembled and internal capsule surface and components were clean. All of the alumina, Lucalox specimens had turned from the characteristic milky-white appearance to a dark-gray color. The alumina isolation insulator also experienced a darkening but not to the same degree as the Lucalox. The change in color of the alumina material is believed to be associated with the production of F or V color center irradiation defects. With the exception of one sample in which some breakage of the alumina was observed as a result of slight misalignment, all of the alumina appeared to be crack free while in the electrode assemblies. Upon removal of the Lucalox specimens from the electrode assemblies, three of the specimens were bonded to the Kovar electrodes and of these three, two specimens had evidence of cracking. Of the five specimens that were freely removed from the electrode assemblies, four of them were crack free while the remaining specimen had a circumferential fracture at the internal flange. A comparison of the pre- and post-dimensional measurements revealed no change. Metallographic observations of the alumina did not reveal any irradiation changes in the microstructure.

DEVELOPMENT AND EVALUATION OF CYLINDRICAL THERMIONIC CONVERTERS

This development task on cylindrical thermionic converters was divided into two phases. In Phase I, seven cylindrical converters with concentric tungsten emitters and niobium collectors were successfully constructed and tested for a cumulative total of 24,672 hours with an average test time of 3525 hours. The two shortest test times were 100 and 916 hours. All other converters operated well into the thousands of hours. The longest run was 8055 hours. In each case, after initial performance mapping the converter performance achieved equilibrium and was essentially constant over the converter lifetime.

The total test times achieved by each of the seven converters built and tested under the first phase of this program are listed below.

Converter Number	Emitter Material	Collector	Spacing (Mils)	Hours
301	CVD Tungsten*	Niobium	10	3574
302	CVD Tungsten	Niobium	10	100
303	CVD Tungsten	Niobium	10	916
311	CVD Tungsten	Niobium	10	6413
312	CVD Tungsten	Niobium	10	8055
313	CVD Tungsten	Niobium	10	3775
331	CVD Tungsten	Molybdenum	10	1839

*Chemical Vapor Desposited Tungsten

[redacted]

All tests, with one exception, were terminated because cesium leaked into the electron bombardment heating equipment through a tantalum isolation thimble. The presence of cesium resulted in positive ion bombardment of the filament and rapid filament failure. The isolation thimble could not be repaired and the tests were terminated.

The results of the post-test examinations revealed that leakage of cesium was not associated with any failure of converter components but was a failure of the method of heating the converter. The electron bombardment heater was contained in a tantalum sheath that was slipped into the tungsten emitter. The interdiffusion of tantalum and tungsten left porosity in the tantalum sleeve, which eventually leaked cesium into the electron bombardment vacuum cavity and caused the heater to fail. The one test failure caused by a converter component was in converter 303 which operated 916 hours. At that time an intermittent emitter-to-collector short circuit occurred. Subsequent post-test examination indicated the short circuit was caused by contamination within the tungsten emitter structure. This contamination was sandwiched between the layers of the "two-pass" vapor deposited tubing. Operation of the faulty material at emitter temperatures caused the emitter to swell and caused an emitter-to-collector short circuit by bridging the interelectrode gap. This problem, having been identified, was prevented from possible reoccurrence in subsequent converters by specifying emitter tungsten tubing made by single pass vapor deposition techniques.

In analyzing the results from this out-of-pile converter program, it can be concluded that the objectives were clearly achieved. A converter and supporting components which closely simulated a converter designed for a thermionic reactor was achieved through an evolutionary program of design, fabrication and testing. The dimensional stability of the converter components was excellent. The integrity of the spacing devices and the intercell components was very good. Repeatable fabrication of converters with reproducible performance characteristics was obtained. Performance tolerance on earlier converters was slightly in excess of $\pm$ 10% and was narrowed in subsequent devices with continuing fabrication and processing refinements. The predominant reason for test termination was cesium leakage into the electrical heater through a tantalum sheath and not any component of the thermionic converter.

The purpose of the second phase of the program was to investigate the effect of UO_2 fuel on thermionic performance, to determine the nature and extent of any resulting material interactions and to investigate the thermionic performance characteristics of tungsten-25 w/o rhenium emitters in cylindrical thermionic converters. This investigation was conducted by the life testing of two fueled thermionic converters.

The emitters swelled and shorted the converter in a few hundred hours. The reason for this failure was not fully understood. However, the test results indicated that for short lifetimes there are no deliterious effects on thermionic performance due to the presence of UO_2 and none may be expected as a function of time. There was no evidence of tungsten-25 w/o rhenium-UO_2 incompatibility. The converter performance levels achieved with W-25 w/o Re emitters, Mo collectors, and 10-mil spacing compare very favorably with the performance achieved with a 5-mil tungsten/nickel converter of the same generic design. Therefore, a program to develop a UO_2 fueled emitter for out-of-core testing was not required.

IRRADIATION OF UO_2 FUEL/CLAD WITH TUNGSTEN-25 W/O RHENIUM

An irradiation experiment was performed to determine the characteristics of bulk UO_2 fuel specimens clad with W-25 w/o rhenium in a configuration representative of a nuclear thermionic converter for space power reactors. The specific objectives of the experiment were:

(1) Achieve a fuel burnup greater than 1×10^{20} fissions/cm^3 with a clad temperature of 1650°C,

(2) Measure the amount of fission gases that escapes through vent holes in the end cap,

(3) Measure the quantity of UO_2 that escapes through the vent holes,

(4) Obtain information on the behavior of fission products,

(5) Determine the structural integrity of the fuel/clad specimen, and

(6) Determine the UO_2–W–25 w/o Re compatibility in a nuclear environment.

The experiment capsule was designed to accommodate four irradiation specimens. The dimensions of each fueled emitter were 0.456-inch in diameter by 1.350-inches long with an emitter thickness of 0.20-inch. Three 0.020-inch vent holes were located in each end cap of the cylindrical cladding. The four specimens were positioned in pairs, each pair was mounted vertically in the capsule. The two upper specimens were designed for fuel enriched to 2.4% while the lower specimens were designed for fuel of 1.5% enrichment. These enrichments were calculated to obtain equal power in the specimens based on the vertical neutron flux gradient in the Plum Brook Reactor. The upper and lower specimen pairs were unknowingly switched during capsule assembly, causing the lower specimen to operate at twice the power density of the upper specimens during the irradiation. The space between the fuel/clad and the containment

can of each specimen was filled at room temperature with one atmosphere of 75% argon—25% helium gas to conduct the heat from the clad to the containment can and maintain the proper temperature drop. The temperature of each fueled specimen was determined by measuring the support stem temperature and then using a calibration curve which relates the stem temperature to the clad temperature. An out-of-pile calibration experiment and calculations of in-pile gamma heating were used to establish the calibration curve. The capsule position was varied during the irradiation to maintain the lower specimen clad temperature at 1650°C.

The capsule was installed in test location LD-11 of the Plum Brook Reactor. The operating data from the first cycle showed that the lower specimen temperatures were much higher than expected. Therefore, the capsule was moved to the LA-11 test location where the neutron flux was lower. In this location, the lower specimens could be maintained at a calculated clad temperature of 1650°C during a normal reactor operating cycle. Analytical studies were performed to resolve the uncertainties in the clad temperature and thermal power of each specimen. The standard deviation of the 1650°C clad temperature was calculated to be 110°C and of the 350 watts thermal power was calculated to be 70 watts. Throughout the capsule (on-test) operational history, the lower specimens were maintained essentially at a constant clad temperature (based upon certain thermocouple indications). However, in order to maintain this condition, a continual increase in capsule operating flux level was required.

The capsule endured 41 temperature cycles during its operational history; and the capsule, in a fully retracted position, operated with a clad temperature of approximately 1000°C for prolonged periods. The irradiation of the capsule was terminated after a total of 3340 hours at operating temperature because increased heating rates were required to maintain a constant specimen temperature, indicating distortion of the emitter. Significant post-test examination operations and results are given below.

(1) The stainless steel containers were punctured and gas samples were successfully collected from specimens 2, 3, and 4. The gas was analyzed by gamma counting to determine the quantity of Kr-85 in each sample. The results are presented in Table 2 along with the calculated quantity of Kr-85 produced based on actual burnup data.

TABLE 2. Kr-85 Gas Vented

Specimen	Kr-85 Atoms in the Gas Sample	Kr-85 Atoms Produced by Fission	% Vented
2	3.61×10^{17}	4.67×10^{17}	77.3
3	8.87×10^{17}	10.3×10^{17}	86.1
4	8.43×10^{17}	9.53×10^{17}	88.5

(2) Dimensional measurements were made on each fuel/clad and the maximum change in dimensions is presented in Table 3.

TABLE 3. Maximum Dimensional Changes of Fuel/Clad

Specimen	Diametral Change (Inches)	Length Change (Inches)
1	+ 0.024	- 0.002
2	+ 0.013	- 0.001
3	+ 0.050	+0.040
4	+ 0.046	+0.035

(3) The burnup analyses of the UO_2 fuel was done by measuring the quantity of Nd and heavy element fission products in the fuel. These results are presented in Table 4.

TABLE 4. UO_2 Fuel Burnup

Specimen	10^{20} Fissions/cm^3 Based on Nd Measurements	10^{20} Fissions/cm^3 Based on Heavy Elements
2	0.94	0.92
3	2.07	2.16
4	1.92	1.92

(4) The quantity of UO_2 which escaped through the vent holes in specimen 4 was determined to be 1.94 mg which is less than 0.01 percent of fuel in one specimen. The vent holes in all specimens were completely open and only a trace of UO_2 was detected in the vent hole of Specimen 3.

(5) The UO_2–W-25 w/o Re interface was completely separated with no evidence of bonding and no chemical interactions. The cladding was expanded but there were no cracks in the clad material.

A thorough examination of the post-test data and operational history indicates that the clad deformation may have resulted from thermal-mechanical interaction between the UO_2 fuel and the cladding. The proposed mechanism is described as follows.

(1) The UO_2 fuel redeposits during the first few reactor cycles, such that the fuel and clad are in intimate contact at a given power density and temperature.

(2) Then if the specimen is operated at a lower power density, the temperature is reduced and a gap forms between the fuel and clad because of difference in coefficients of thermal expansion.

(3) The UO_2 fuel would then redeposit and be in intimate contact with clad at a lower temperature than initially.

(4) Then if the specimen power density is increased to bring the clad temperature up to the original temperature, the clad would be expanded because the UO_2 thermal expansion is greater than the W-Re clad.

(5) Each succeeding power density change of this type resulting in a major temperature change (200°C) would incrementally expand the clad.

(6) The overall increase in clad dimensions would then be determined by the number of major temperature changes made during the operating life of the specimens.

ASSESSMENT OF THE PROGRAM

This thermionic development program has resulted in advances in key technology areas.

Cylindrical converters were designed, fabricated and tested. Long term operation with stable and constant power outputs was demonstrated and the output powers obtained are consistent with the design requirements of projected in-core thermionic reactor systems. A lifetime of 8055 hours was achieved on one converter. The limiting factor on the lifetime of this converter and all but one of the others was the failure of the electron bombardment heater, an auxiliary item characteristic of out-of-pile testing and completely unrelated as a limiting factor in nuclearly heated converters. Intercell components were also designed, developed and tested successfully. This intercell design was incorporated in a three-cell thermionic fuel element and was used with success under an AEC fuel element development program.

Compatibility between the nuclear fuel, bulk UO_2, and W-25 w/o Re (one of the candidate emitter-clad materials) was demonstrated under thermionic operating conditions. Cracking of the clad material occurred in the 60 and 70 v/o UO_2-W cermets clad with W-25 w/o Re. The problem may be related to the mismatch in thermal coefficient of expansion between the clad and cermet body. These test results indicate that further development work is required before this fuel form is ready for in-pile testing.

The irradiation results of high purity alumina insulators to 1.6×10^{20} nvt fast (>1 MeV) neutron flux indicate no dimensional changes or deleterious effect on electrical properties. While some of the specimens were cracked, the alumina sleeves remained an integral body. Although these results are encouraging, irradiation experiments to fluences of 2×10^{21}* nvt (>1 MeV) and greater are necessary to ascertain the effects of irradiation on the properties of alumina.

Irradiation of UO_2 fuel clad with W-25 w/o Re to burnups of 2.16×10^{20} fissions/cm^3 revealed significant dimensional changes which may be attributed to mechanical-thermal interactions between the fuel and the clad. However, there was no evidence of chemical

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* Design projected fluence of 300 kW(e) fast spectrum reactor.

incompatibility between the UO_2 and the clad. Further, the vented emitters operated with low loss rates of UO_2 fuel and high release rates of fission gases (75%). This experiment indicates the need for more fuel/clad in-pile experiments to determine the behavior of fission products, dimensional stability of the fuel/clad specimen, UO_2 fuel redistribution behavior, and fission gas release.

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